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JAYCOR

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MASTER

ASSESSMENT OF SCALING LAWS AND
PROPAGATION WINDOWS FOR FOCUSING
OF ION BEAMS IN FUSION
TARGET CHAMBERS

FINAL REPORT

April 1980

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ABSTRACT

Intense beams of multi-GeV high atomic weight ions are being actively investigated as possible ignitors for pellet fusion reactors. Over the past year we have developed beam transport models for the final focussing of these beams in the reactor chamber, and investigated the role of micro-instabilities, filamentation, conductivity, multiple scattering, and knock-on electrons. Two propagation windows exist, namely the vacuum window at pressures below about $10^{-3} - 10^{-4}$ torr and a window around 1 torr. The 1 torr window (which is desirable from a reactor viewpoint) became less certain this year due to our discovery of the major role played by knock-on electrons which are sufficiently numerous to produce a reversed (ion-defocussing) magnetic field ahead of the ion pulse. Unless most of the knock-on current is wiped out by self-fields, this effect appears to eliminate use of self-pinched ion beams, and may degrade ballistic mode spot sizes as well. Intermediate energy knock-on electrons ($0.3 \lesssim v_z/v_b \lesssim 1$) may also dominate the electrical conductivity in the ion pulse, and will influence micro-instability and filamentation calculations.

1. TECHNICAL DISCUSSION

Intense ion beams are being actively pursued as potential ignitors for pellet fusion reactors. Possible choices range from accelerators delivering pulses of 5-20 GeV heavy ions such as uranium, down to 10 MeV light ion beams generated in diode configurations. The stopping range of the beam in the target determines the useful upper limit to the beam energy. These fusion systems require that the beam be focussed to a radius of ~ 0.1 cm in traversing the final 5-10 m from the wall of the target chamber to the pellet.

Over the past year we have developed beam transport models for the final focussing of heavy ion beams through the reactor chamber gas, and investigated the role of micro-instabilities, filamentation, multiple scattering, and knock-on electrons. Two propagation windows appear to exist, namely a fairly secure vacuum window at reactor vessel pressures below about 10^{-3} to 10^{-4} torr, and a less certain window in the neighborhood of 1 torr. The ~ 1 torr window (which would be desirable, but not necessary, from a reactor viewpoint) became less secure this year due to our discovery (originally pointed out by S. Goldstein of our group) of the major role played by knock-on electrons, and this effect may for example eliminate the use of ion beams in a pinched propagation mode. Knock-on electrons form two important groups, - the less numerous population that outruns the ion beam and may set up a self-pinched channel ahead of the pulse, and the highly numerous intermediate energy group ($\sim 0.1 - 10$ keV) which co-exists with the ion beam and may dominate the conductivity while cancelling much of the ion beam current directly. This latter group is expected to make considerable changes in any part of the physics involving electron transport or conductivity. Examples include filamentation instability and anharmonic

emittance growth in focussed beams, as well as zero order self-magnetic field effects in both focussed and pinched beams. These questions are currently being investigated.

In the proposed continuation of this work we plan to further refine our models of the plasma window at 1 torr with its associated scaling laws, and also to give greater emphasis to work on the location of the high pressure edge of the vacuum window, i.e., determine how rarefied a vacuum is required in order to avoid plasma effects entirely. This involves clarifying the physics of electrostatic trapping of electrons in the beam well, two stream instability for $n_b > n_e$, anharmonic effects (recently pointed out as important by the Livermore group), and charge stripping cross-sections at low pressures.

The current status and ongoing activities of our group to date can be summarized as follows:

a. Knock-on Electrons:

For typical reactor chamber conditions ($\beta_b \sim 0.4$, 1 kA per beam, $p \sim 1$ torr), the high current heavy ion beams proposed as drivers for pellet fusion will produce large currents of knock-on electrons with $v_z \gtrsim \beta_b c$, the beam velocity. The current I_k carried by these electrons, which are produced by nearly head-on collisions between beam ions and ambient electrons, usually exceeds the beam particle current and can exceed the ~ 10 kA Alfvén limiting current. Some of these electrons form a broad self-pinched "beam" which outruns the ions and creates a plasma channel whose magnetic field deflects some (or probably all) of the beam ions outward. Based on simple models for the knock-on "beam" radius, these deflections lead to a serious increase in spot size for $p \gtrsim$ a few torr in He.

The quasi-equilibrium model used to estimate the knock-on beam radius assumes that $I_k < I_A$ and that the knock-on current is not reduced by collisional or self-field effects. Although these two assumptions may apply to a 20 GeV ion beam propagating in Helium at 1 torr, most recent reactor scenarios involve substantially lower beam energies (5-10 GeV) and heavier target chamber gases. In the absence of self-fields, a 1 kA, 5 GeV Uranium beam propagation in 1 torr of Ne accumulates a knock-on current exceeding $I_A \sim 6$ kA in less than 10 cm. However, due to their relatively lower energy (10-20 keV) and the presence of stronger magnetic fields, these knock-on electrons will not accumulate freely, and a completely different physical model must be used.

The more numerous population of slower knock-ons (with $v_z \lesssim \beta_b c$) cannot contribute to the defocussing channel ahead of the beam but may dominate classical transport inside the beam. It has been generally assumed that the bare ion beam current is almost completely balanced by a return current carried by the $\lesssim 10$ eV bulk electron population generated by ionization of the background gas. However, energetic secondary electrons (including knock-ons and stripped "drop-off" electrons) may modify this picture completely. First, electrons with $v_z \gtrsim 0.3 \beta_b c$ may directly cancel most, if not all, of the ion beam current directly, especially if the $B_\theta < 0$ field from the prechannel persists. In addition, the energetic tail of the bulk plasma distribution may be sufficiently well populated to carry this reduced return current, thereby increasing the effective conductivity considerably. If this scenario is correct, any magnetic field near the head of the beam will tend to be rapidly frozen in. This would completely change classical transport as well as influencing filamentation and two-stream instability calculations.

b. Beam Transport Code:

This code is now up and running. The code has been completely re-written to eliminate the quasi-static approximation used in earlier versions.

c. Filamentation:

The electromagnetic filamentation instability is expected to occur in heavy ion beam fusion target chambers. For a converging beam, the instability is expected to be convective with group velocity v_g approaching the beam velocity V_b until the beam is 10-50 cm from the target. The number of e-foldings N_Y is estimated by integrating the local growth rate along the beam trajectory. For a cold beam, the result agrees with the initial value problem solution of Lee, et al. Detailed numerical solutions to the full dispersion relation predict somewhat lower values for N_Y . Close to the target, $v_g \rightarrow 0$, and the instability is effectively nonconvective, with N_Y proportional to the pulse length. If a realistic conductivity model is used ($\sigma \propto (Z_b/R)^2$) the number of e-foldings in the nonconvective region is generally smaller than N_Y in the convective region. Thus, any appreciable deterioration in beam quality is more likely to occur while the beam is in the convective region.

d. Propagation Windows:

Various composite plots that display the windows for which instability-free propagation and focussing occurs have been prepared. The boundaries include return-current, two-stream, and filamentation instability, together with the constraints set by orbit deflections from self-consistent B_θ , anharmonic emittance growth, classical scattering, and knock-on electrons. These results have been reported at presentations to the Foster and Jason

committees and is an ongoing process subject to constant revision as our models become more refined.

e. Nonlinear Filamentation Instability (2D Spectral Code):

Drs. Glenn Joyce and R. Hubbard have had considerable experience with 2D spectral density codes which have proved useful in studies of fluid turbulence. Some time was spent attempting to explore the nonlinear evolution of beam-driven filamentation instability using these methods but difficulties were encountered (the local density goes negative before saturation is reached), so that this investigation has been discontinued temporarily.

f. Propagation at Low Pressures:

Given the complexity of the ~ 1 torr window, it is important to determine as accurately as possible the maximum allowable pressure for vacuum propagation. Based on atomic physics data from Gillespie, et al., we have estimated plasma densities and beam charge states at pressures below 10^{-3} torr. At pressures below about 10^{-4} torr, the beam remains largely unstripped, and the plasma density n_e is less than the beam density n_b . Thus, most of the plasma physics complications are avoided, although beam space charge effects may present problems for low energy beams (~ 5 GeV). For somewhat higher pressures ($10^{-4} - 10^{-3}$ torr), the situation is somewhat more complicated. The beam charge state may rise to 2 or 3, and $n_e \sim n_b$. The two-stream instability probably saturates by electron heating, but field amplitudes are limited by the relatively small number of available electrons. This regime is compatible with lithium waterfall reactor designs and is likely to be the most desirable scenario. At higher pressures, rapid charge stripping and ionization of the background lead to much stronger

two-stream amplitudes and more complicated transport physics.

Based upon our work and studies by related groups in the field, a number of new questions concerning heavy ion beam transport have arisen. Many of these issues were raised at the recent Berkeley workshop and are related to the trend to lower beam energies (5-10 GeV) dictated by recent pellet calculations and the major role played by knock-on electrons.

1. Can ballistic propagation at 1 torr be saved as a viable option?

Recent studies by the Livermore group indicate that anharmonic effects lead to an unacceptable growth in emittance. Also, filamentation instability is considerably more dangerous at 5 GeV than at the higher energies considered previously.

2. Do knock-ons eliminate the possibility of self-pinch propagation?

To answer this question requires accurate estimates of the knock-on current and conductivity inside the beam. It remains an open issue.

3. Will knock-on electrons actually propagate in the presence of self-fields? Much of the knock-on current will be reduced due to self electric and magnetic fields. This is especially true near the head of the ion beam. However, this problem is highly non-local due to the large spread in knock-on velocities and is strongly coupled to local plasma densities and conductivity. Even qualitative estimates of knock-on current in the presence of self-fields are difficult to make at this time.

4. To what extent can conductivity be raised or effective beam current reduced by energetic secondary electrons? This question has already been

addressed qualitatively but quantitative estimates require much more effort.

5. What is the effect of the distribution of beam charge states?

Simple estimates indicate that this problem could seriously degrade ballistic focussing spot size.

6. How does the two-stream instability couple to conductivity generation and the macroscopic fields in the $n_e \gg n_b$ regime? Particle simulation studies by Les Thode at LASL have begun to address this question. In addition, John Guillory of our group has developed a simple model of this coupling process for relativistic electron beams. It appears that Guillory's model can be adapted to the heavy ion beam classical transport code.

7. What physics determines the location of the vacuum window? Charge stripping, space charge effects, and the two stream instability may all play a role, but detailed analysis has not yet been performed.

8. How serious are space charge effects in the vacuum regime and are co-moving electrons required to provide some charge neutralization? Serious deflections may occur due to radial electric fields during propagation or due to the buildup of charge on or near the pellet. These problems have become potentially serious with the lower energies and higher currents required by recent pellet calculations.

9. Is propagation possible in a 10^{-3} - 10^{-4} torr Lithium waterfall chamber? In this regime, plasma effects and charge stripping are just beginning.

10. What propagation effects can be simulated experimentally, with existing light ion beam technology? In view of the complexity of the

transport problem, experimental verification of some of the theoretical predictions is extremely important.

2. TECHNICAL APPENDICES.

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